

# Diverse responses of different structured forest to drought in Southwest China through remotely sensed data

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## ABSTRACT

Global climate change leads to gradual increases in the frequency, intensity, and duration of extreme drought events. Human activities such as afforestation and deforestation have led to spatial variation in forest structure, causing forests to exhibit an age-spatial structure relationship. Thus, it is of great importance to accurately evaluate the effects of drought stress on forest ecosystems with different forest age structures. Because the spatial heterogeneity varies with drought stress intensity, forest age, there are still a lot of uncertainties in current studies. In this study, based on the field measurement, and the proxy index of stand age (based on forest canopy height from LiDAR and stock volume from inventory) at the regional scale, we analyzed the different drought responses of forest ecosystems with various forest ages across different scales in Yunnan province, southwest China from 2001 to 2014. At the local scale, significant differences in the effects of drought stress were found among forests with various ages, suggesting that older forests suffer more under drought stress than younger forests. At the regional scale, the investigation statistics of forest damage indicated a maximum damage ratio in the forest with tall trees (> 32 m), whereas damage was minimal in the forest with short trees (< 25 m). The stock volume of the forest exhibited the same pattern, that is, the forest damage ratio increased as the stock volume increased. These data demonstrate that the responses of forest drought could be affected by forest age. Under drought stress, older forests show greater vulnerability and risk of damage, which will require special attention for forest managers, as well as improved risk assessments, in the context of future climate change.

## 1. Introduction

In the context of global climate change, the frequency, intensity, and duration of drought stress have gradually increased (Cook et al., 2014), which substantially impact the structure and function of forest ecosystems (Choat et al., 2012). Drought not only affects the vigor and growth of trees, but also induces tree death and forest degradation (Choat et al., 2012). The effects of drought on forest ecosystems are multifaceted, and can include decreases in forest productivity (Ciais et al., 2005) and advancement of the dormant period (Xie et al., 2015). Accordingly, trees respond to drought stress by adjusting the growth of their root systems, and by reducing stomatal conductance and leaf area (Nepstad et al., 1994; Delzon and Loustau, 2005; Niu et al., 2014). Forest ecosystem responses to drought and their internal adjusting

mechanisms vary according to drought intensity and duration (Niu et al., 2014), which add to the uncertainty of forest responses to drought (Guarín and Taylor, 2005; Nepstad et al., 2007). In addition, human activities such as deforestation and afforestation also increase the variation in forest attributes such as forest age structure. Therefore, to better mitigate and adapt to the impact of human activities and climate change on forest ecosystems, a more accurate evaluation of drought stress in forests with different attributes (such as forest age) is required (Piao et al., 2011; Steinkamp and Hickler, 2015).

Lack of rainfall is the primary cause of droughts, and precipitation is the most direct index for analyzing the characteristics of drought. When evaluating the intensity of drought, multiple indexes for drought assessment have been constructed using precipitation and temperature data. The Standardized Precipitation Index (SPI), mainly based on

Abbreviations: EVI, enhanced vegetation index; ED, EVI deficit

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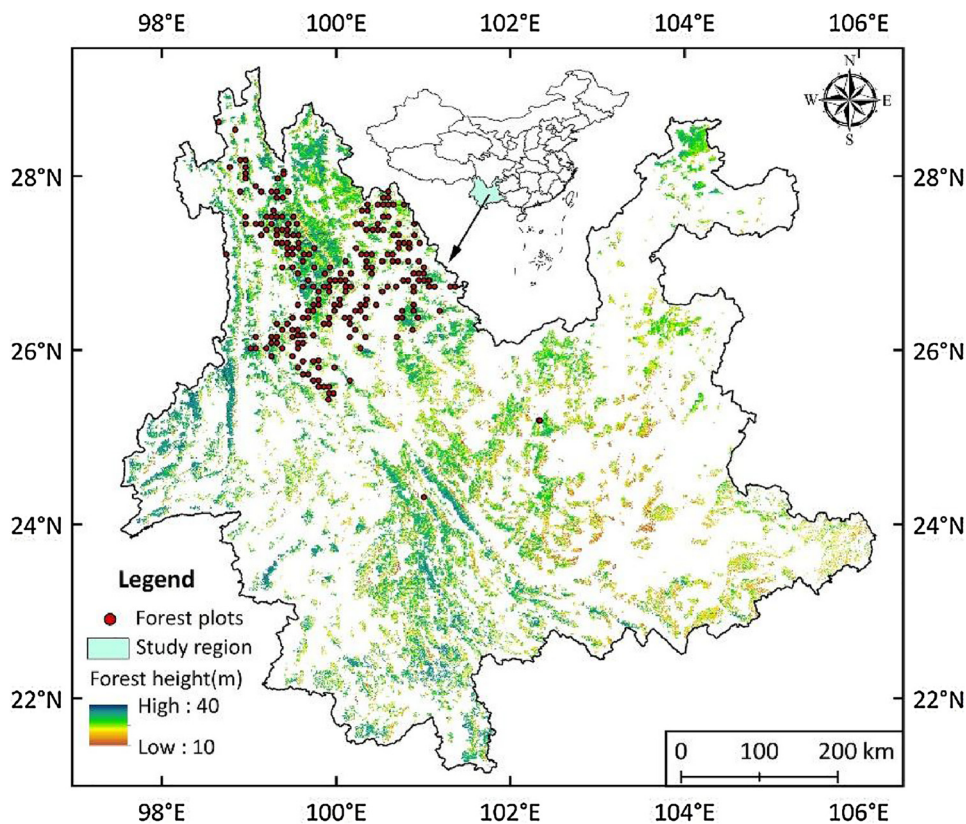


Fig. 1. The spatial location and the distribution pattern of forests in the study region. The forest distribution was obtained from the 7th Inventory of National Forest Resources (State Forestry Administration, 2010a), forest height was from Simard et al. (2011) and the field measurement of forest age was as described in Guo and Ren (2014).

precipitation data, is easy to calculate and can be utilized to indicate drought at different time scales (McKee et al., 1993). Without precipitation, the temperature increases which leads to water evaporation, aggravating the drought intensity (Sheffield and Wood, 2008). Therefore, the drought indexes that contain temperature information, such as Palmer Drought Severity Index (PDSI) and standardized precipitation evapotranspiration index (SPEI), are more useful for analyzing drought characteristics (Sheffield and Wood, 2008). Due to the time hysteresis (Wu et al., 2015) and the accumulative effect (Huang et al., 2015) of climate responses in plants, it is necessary to apply a meteorological index at multiple time scales for drought evaluation (Li et al., 2015; Huang et al., 2015; Luo et al., 2016). As SPEI integrates both the advantages of PDSI (where the effect of temperature trends and fluctuations in evaporation are considered) and SPI (which is easy to calculate and multiple time scales are considered), it is widely used at global and regional scales (Vicente-Serrano et al., 2010).

The differences in forest attributes constitute another important reason that forests differ in their responses to drought. The age of forests, age-related tree height, and stock volume all significantly affect the water absorption and consumption of trees. Previous research demonstrated that soil water was less available to small trees with shallow roots compared to its availability to large trees with developed root systems, thereby making small trees more sensitive to drought stress (Guarín and Taylor, 2005; Nakagawa et al., 2000). Other studies have revealed that water transportation paths are longer in large trees, that their consumption is higher to maintain respiration, and that evapotranspiration on the leaf surface is more vigorous in large trees, which leads to a higher water demand; thus, drought would appear to have a greater impact on large trees (Nepstad et al., 2007). The forest age is an important reference index in all the attribute factors influencing forest water balance. According to the growth theory of trees, diameter at breast height (DBH), tree height, and stock volume are all related to forest age (Zhang et al., 2014), and these factors are reflected in the photosynthetic and productive activity of forests (Zhou et al., 2013; Zhou et al., 2015). Human activity (such as afforestation) is a

significant driving factor in changes to forest age, so revealing the differences in drought responses of forests with various forest ages may facilitate better management to control forest damage risk in future climate change. At the regional scale, the drought response of forest can be affected by the spatial heterogeneity of the meteorological drought index and the intrinsic forest attributes. Thus, the influence of spatial heterogeneity for meteorological drought should be removed to reveal the effect of vegetation attributes (such as forest age) on the response to drought stress (Luo et al., 2016).

Remote sensing technology, which is a high-efficiency modern data acquisition tool, could provide data with high spatial and temporal resolution for forestry research (Assal et al., 2016; Dorman et al., 2013; Xie et al., 2015). The optical properties of green vegetation, which shows strong absorption in the red wave band and strong reflectance in the near infrared wave band, allows for easy calculations of metrics to identify changes in vegetation. Multispectral sensors mounted on different satellites provide a wealth of reflectivity data for studies on the earth's surface. For example, the moderate-resolution imaging spectroradiometer (MODIS), mounted on the satellites of Terra and Aqua, supplies data for various vegetation indices based on the calculation of remote-sensing reflectance, which is widely used in the study of ecology. Of these, the most commonly used index is the normalized difference vegetation index (NDVI) and enhanced vegetation index (EVI). Compared with NDVI, EVI is more adapted to study areas with high vegetation coverage at the regional scale (Matsushita et al., 2007). Trees respond to drought stress by reduce leaf area (Nepstad et al., 1994), which could be reflected in the information from satellite observation (Huang et al., 2015).

In this study, by integrating field measurement data, remote sensing data, national forest inventory data, and climate data, we analyzed the drought responses in different forests with various forest ages, stock volumes, and canopy height at local and regional scales to reveal different drought responses in forests of different forest ages. The objectives of this study are to solve two scientific questions: Eliminating the interference of spatial heterogeneity, 1) do differences in forest age

significantly affect forests' response to drought, 2) and is there a consistent pattern over different spatial scales?

## 2. Data and methods

### 2.1. Study region

The study region is located in Yunnan Province in southwest China (Fig. 1). The total area is 390,000 km<sup>2</sup> (97.51–106.18°E and 21.13–29.25°N) with an annual average temperature of 16 °C, annual precipitation of 1105 mm (Luo et al., 2016). In recent years, several severe drought events occurred in Yunnan province, especially a short drought event in 2005 and a long drought event during 2009–2013, which had substantial effects on the local forest ecosystem (Luo et al., 2016).

According to the 8th National Forest Resources Inventory, Yunnan has abundant forest resources with a forest coverage rate of 50.03% (<http://211.167.243.162:8085/8/index.html>), a total forest area of 19,140,000 ha and a stock volume of 1,693,090,000 m<sup>3</sup>. Since the 20th century, the “Grain for Green” program (GGP) (Xiao, 2014) has been implemented in Yunnan, and planted forest area accounted for 23.71% of the total forest area. The planted forest complicates the structure of forest age, and young forests account for 34.92% of the total forest area (Fig. 2a). The main forest types in Yunnan include broad-leaf mixed forest, Yunnan pine, oak forest, mixed coniferous broad-leaf forest, conifer mixed forest, and other firs (Luo et al., 2016). Because of the recent drought events in Yunnan (Fig. 2b based on SPEI) and its complicated forest age structure, it provides the ideal region to study the effects of forest age on drought responses.

### 2.2. Field measurement data

In order to analyze the different effects of drought on forests with various forest ages, we collected data from 230 forest plots with various ages (aged 10–200 years) in the study region used in the previous studies (Guo and Ren, 2014). The data included geographic location, elevation, forest type (mainly dominated by pine and spruce), forest age, DBH, height, and stock volume. The tree size variables are strongly correlated with age (Fig. 3), providing the basis for the present study to use tree height and volume as proxies for forest age at the regional scale. Considering that the plantation forest was greatly affected by human activities, we only collected plots from natural forests to show the drought effects resulting from climate fluctuations.

### 2.3. Remote sensing data

To demonstrate the effect of drought stress on vegetation, we applied the product of MODIS EVI (MOD13A1) (<http://modis.gsfc.nasa.gov/>).

Though the normalized difference vegetation index (NDVI) is sensitive in monitoring areas with medium and low vegetation coverage, it is easily saturated in the areas with high vegetation coverage. The EVI formula incorporates the blue waveband to improve the vegetation signals, staying sensitive and unsaturated even in the area with extremely high vegetation coverage (Gao et al., 2000; Huete et al., 2002). Due to the high vegetation coverage in the present study, we chose MODIS EVI to better reflect the dynamics of forest vegetation in the study region. Considering that tree growth is sensitive to water availability (Huang et al., 2015; Luo et al., 2016), the data utilized in the present study were the 193rd–241st days (covering the growing season from July to August, four images) each year from 2001 to 2014, with spatial resolution of 500 m and temporal resolution of 16 days. EVI falls in the range from −1 to 1. According to the reliably data set, the average proportion of useful EVI pixels (include good data and marginal data) to the total was over 50% in the study area from 2001 to 2014, and the highest proportion was 68% in 2006.

At the local scale, forest height and stock volume are strongly correlated with age (Fig. 3), and as a result, the forest height could be used as a proxy to estimate the forest age at regional scale (Zhang et al., 2014). In this study, we used the spatially-specific forest height data (1 km resolution) (Simard et al., 2011), which derived from the LiDAR, as the proxy for forest age at the grid level. The dataset of forest height downloaded at <http://lidarradar.jpl.nasa.gov>, and it was well correlated with the height data from field observation in Yunnan and southwest China (Zhang et al., 2014).

### 2.4. Forest inventory data

At the regional scale, we used the spatial patterns of the forest stock volume from the 7th National Forest Inventory (Administration, 2010a) as the proxy for forest age to study different drought responses in the forest with various levels of stock volume. The stock volume of forests in Yunnan was categorized into five classes (< 30 m<sup>3</sup>/ha, 30–60 m<sup>3</sup>/ha, 60–90 m<sup>3</sup>/ha, 90–120 m<sup>3</sup>/ha and ≥ 120 m<sup>3</sup>/ha). To match inventory data to other data in the present study, the source images were scanned and digitized, then the spatial registration and resolution adjustment were performed.

### 2.5. Drought indicator data

To reveal the different effects of various drought intensities on forests, we employed the Standardized Precipitation Evapotranspiration Index (SPEI) as the indicator for drought intensity in the present study. SPEI is the widely used index (Vicente-Serrano et al., 2010, 2013) to quantify surface water deficit and surplus (Beguería and Vicente Serrano, 2016). In this study, the SPEI data were obtained from the global SPEI data set, which is based on monthly precipitation and

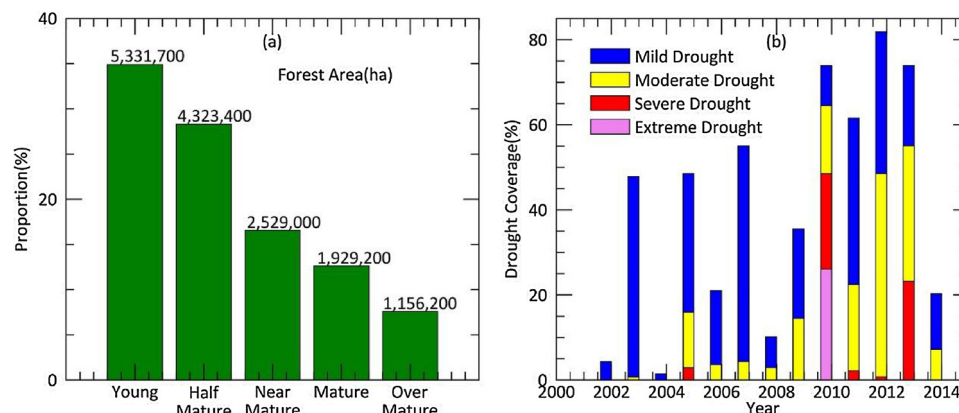


Fig. 2. (a) The characteristics of forest age in Yunnan, (b) the scope and intensity of the drought stress in recent years.



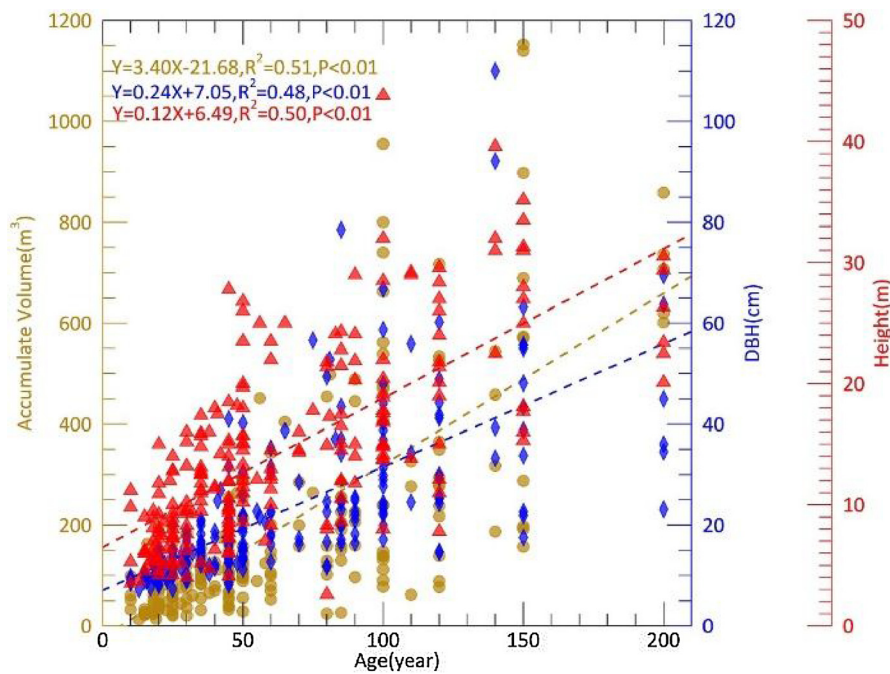


Fig. 3. The relationship between DBH, forest height, and stock volume with age.

potential evapotranspiration from the Climatic Research Unit (CRU) of the University of East Anglia (<http://sac.csic.es/spei/database.html>). The estimation of potential evapotranspiration in SPEI is based on the FAO-56 Penman-Monteith equation. It provides SPEI timescales between 1 and 48 months, with a  $0.5^\circ$  spatial resolution and a monthly temporal resolution. In the study region, July is the peak month of forest growth (Luo et al., 2016). In order to correspond with the time of the vegetation index, this study utilized July from SPEI with 12-month time scales (Dorman et al., 2013; Huang et al., 2015). According to the classification of SPEI, the water condition can be divided into nine grades: extreme drought ( $\text{SPEI} < -2$ ), severe drought ( $-2 < \text{SPEI} \leq -1.5$ ), moderate drought ( $-1.5 < \text{SPEI} \leq -1$ ), mild drought ( $-1 < \text{SPEI} \leq -0.5$ ), normal ( $-0.5 < \text{SPEI} \leq 0.5$ ), mild wet ( $0.5 < \text{SPEI} \leq 1$ ), moderate wet ( $1 < \text{SPEI} \leq 1.5$ ), severe wet ( $1.5 < \text{SPEI} \leq 2$ ), extreme wet ( $\text{SPEI} > 2$ ) (McKee et al., 1993; Paulo et al., 2012). The threshold for wet condition in SPEI is 0.5 that is water surplus, and for dry condition is  $-0.5$  that is water deficit.

All the spatial data projections were converted to WGS84 coordinate system. The match of EVI data and forest plots had 500 m resolution. The rest of data match were resampled to 1 km resolution by the nearest neighbor algorithm.

## 2.6. Analysis of drought effect at field measurement level

### 2.6.1. EVI deficit in the growing season

Drought stress alters the density of forest canopy (Nepstad et al., 1994; Delzon and Loustau, 2005), and this change is shown in the change of vegetation index from satellite observation (Huang et al., 2015; Luo et al., 2016). The leaf area of the canopy is also different in the forest with different size and cover (Kneeshaw and Bergeron, 1998; Xiao, 2014), resulting in substantial spatial variation in EVI. Therefore, it is difficult to distinguish the effects of external environmental stress from the effects of differences in forest attributes when directly comparing EVI or the absolute amount of EVI variation. To evaluate the effects of the external environment on forest ecosystems in a more accurate manner, the effects of forest attributes need to be removed at different spatial grid points. In the present study, we proposed the relative amount of forest growth variation at each spatial grid (EVI Deficit, ED) as the indicator for the drought response of vegetation. As

there was positive relationship between EVI and SPEI in the study area (Luo et al., 2016), we supposed that without drought stress, forest growth was optimal with the maximum EVI ( $\text{EVI}_{\max}$ ), whereas with drought stress, the observed EVI would be lower than  $\text{EVI}_{\max}$ , and the difference (deficit) increases with growing drought intensity. Thus, the effect of spatial heterogeneity of vegetation attributes can be reduced by comparing the variation of EVI deficit at different grids, which may illustrate the intensity of external drought effects at different grids.

When calculating the ED, the maximum of the average EVI was first calculated for the most vigorous growing season of July–August (Luo et al., 2016) in each year, which shows the forest growth under minimal stress at each spatial grid. Therefore, its spatial difference primarily reveals the effect of the spatial difference in the forest attributes. Second, the difference between the EVI of July–August ( $\text{EVI}_i$ ,  $i = 1 \sim 14$ ) and  $\text{EVI}_{\max}$  and its variation is calculated as  $\text{ED}_i$ , and its interannual variation represents the effect of external factors (such as drought) on EVI, as shown in Eq. (1):

$$\text{ED}_i = \frac{\text{EVI}_i - \text{EVI}_{\max}}{\text{EVI}_{\max}} \times 100\% \quad (1)$$

Where  $\text{EVI}_i$  is the average EVI of July–August at the  $i$ th year,  $\text{EVI}_{\max}$  is the maximum of the average EVI of July–August during 2001–2014, and  $\text{ED}_i$  is the EVI deficit at the  $i$ th year. Because vegetation EVI is greater than 0, the range of ED is  $-100\%$  to 0, and the smaller the ED is, the worse the growing status of the forest is.

### 2.6.2. The effect of forest age on the drought stress of the forest

To study the differences in drought response between forests with various ages, we compared the relationship between age and ED under wet ( $\text{SPEI} > 0.5$ ) and dry ( $\text{SPEI} < -0.5$ ) conditions. First, we took the value of central pixel at sampling plot in the satellite image to calculate the ED average from the window of  $3 \times 3$ , which served as the ED for the corresponding sampling plots. Then, the correlation analysis of the forest age and ED was performed for all the sampling plots. Lastly, the variation in the correlation of forest age and ED was compared under the wet and dry conditions.

Considering the temporal and spatial variations of drought intensity in Yunnan Province (Luo et al., 2016), a paired sample  $t$ -test was used in the present study for quantitative analysis. Specifically, we divided the

sampling plots located in the same SPEI spatial grid ( $0.5^\circ \times 0.5^\circ$ ) into two age groups, with one of younger forests (age < 80) and the other of older forest (age  $\geq$  80) (Guo and Ren, 2014; He et al., 2017), to analyze the effects of forest age on drought stress response. The two age groups have the mean elevation of  $\sim 2800$  m and  $\sim 3100$  m that are below treeline ( $\sim 3900$ – $4200$  m, Liu et al., 2011), the potential impact of elevation was ignored here. Due to the same SPEI grid, the difference of drought stress response for two groups mainly caused by the difference of forest age. In addition, to compare whether there is difference in the effect of forest age between wet and dry conditions, the SPEI grids were grouped into wet and dry condition from 2001 to 2014, and then the *t*-test was employed under each condition.

## 2.7. Analysis of drought effect in the regional scale

Because forest age data were obtained based on ecological observation sites ( $10 \times 10$  m or  $20 \times 20$  m), the data was significantly affected by local site conditions (such as terrain, slope direction, soil properties, and so on). In order to study the effects of forest age at a larger spatial scale, in the present study, we analyzed the differences in drought response of the forest ecosystems with various age-related attributes (forest heights and stock volumes) in the regional scale.

According to the Forestry Department of Yunnan Province (Luo et al., 2016), forests affected by drought are usually divided into two classes based on the level of damage: damaged, and dead. The drought effect is significant when over 10% of the forest area is lost due to drought (damaged), whereas it is severe when the damaged area is over 80% (dead). Studies have demonstrated a strong correlation between the forest damage and the negative anomaly of the vegetation index obtained from satellite observation (Huang et al., 2015; Luo et al., 2016), and the negative anomaly will be reflected in the variation of ED. Therefore, we estimated the ED threshold based on the 2009–2012 ground survey data of resource loss due to drought (damaged and dead) from the Forestry Department of Yunnan Province. To match the ground survey data, ED average was calculated from 2009 to 2012. Then, the cumulative frequency of ED average was classified based on the forest damage and dead rate, and that forest in Yunnan province was divided into three regions, dead region, damaged region, and normal region. Finally, the classified regions were validated by Google Earth and by field investigation (Luo et al., 2016), and the forest height and stock volume were compared among the regions by frequency histograms.

## 3. Results

### 3.1. Comparison of the relationship between forest age and EVI deficit under dry and wet conditions

The SPEI data in Yunnan during 2001–2014 demonstrated that the phenomenon of wet and dry alternation was obvious in Yunnan (Luo et al., 2016). There was no drought occurred in the whole province in 2001 (Fig. 4), and the wet condition in the northwestern region where the sampling plots were located was similar. In contrast, a wide range of drought was seen in 2012 with over 80% of the area exhibiting at least mild drought, and the sample located in northwestern region showing moderate drought (Fig. 4).

The correlation analysis between field measurements and ED (Table 1) illustrated a significantly positive correlation ( $r = 0.18$ ,  $n = 230$ ,  $p = 0.007$ ) between forest age and ED under wet condition in 2001 (SPEI > 0.5), whereas there was a significant negative correlation ( $r = -0.25$ ,  $n = 230$ ,  $p = 0.00016$ ) under the dry condition in 2012 (SPEI < -0.5), indicating that drought stress can induce the reduction of forest ED, affect forest growth. In addition, older forests have greater sensitivity to drought stress.

### 3.2. Drought stress difference in younger and older forests

The comparison of wet and dry conditions (2001 vs. 2012) could reflect the effect of age under different drought stress. As the degree of dry (or wet) condition might also be different, this comparison could not completely eliminate the effect of spatial heterogeneity on drought. To further remove the effect, we designed and applied the paired *t*-test. The forest plots in the same SPEI spatial grid ( $0.5^\circ \times 0.5^\circ$ ), were divided into two groups of younger and older forests to analyze the effects of forest age on drought stress response. This analysis can clarify the differences in drought responses of younger and older forests under the same drought stress (Fig. 5).

The paired *t*-test showed no substantial difference between the growing status of younger and older groups ( $p = 0.883$ ) with wet condition (SPEI > 0.5) (Fig. 6), indicating that the effect of forest age on ED is minimal with sufficient water. However, a dramatic difference in the ED average between two groups was seen with drought stress ( $p < 0.001$ ), and the ED average of the younger group is significantly higher than that of the older group, suggesting that older forests are more susceptible to drought than younger forests. Because the data pairs used in the *t*-test were selected from the same SPEI spatial grid, they had the same water condition. Thus, the difference in the ED average of the two groups resulted from the age variation, indicating that forest age is the primary cause of the difference in ED, that is, the degree of influence in an older forest is greater than that of a younger forest undergoing the same drought stress.

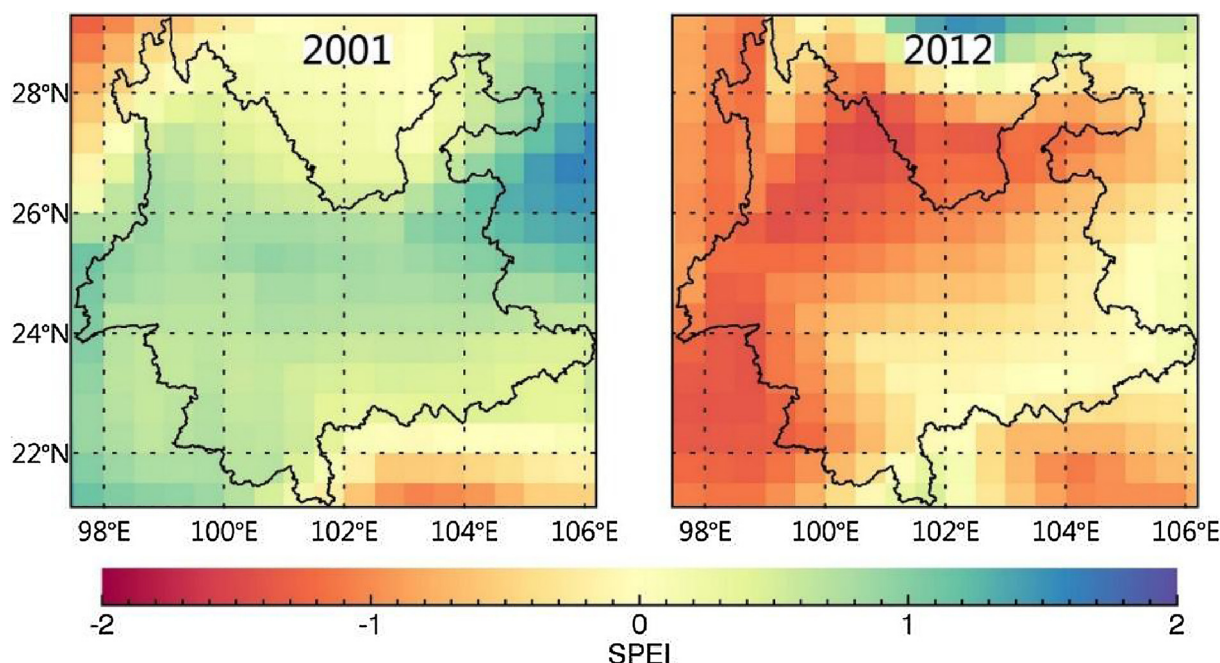
### 3.3. Statistical analysis of drought-affected forests

Yunnan experienced drought for four consecutive years during 2009–2012, affecting a 6,167,000 ha forest area with the damaged area and dead area reaching 4,287,000 ha and 1,880,000 ha (Luo et al., 2016). The total forest area in Yunnan is 18,177,000 ha according to the 7th National Forest Inventory carried out prior to the drought (Administration, 2010b), so the damaged area and dead area accounted for 24% and 10% of the total forest area. Based on the investigation after the drought, along with the variation of ED obtained from 2009 to 2012, the ED average range of the three regions (damaged, dead and normal) area was determined (Fig. 7). The ED average ranges were ED < -26.75% for the dead forest region, between -26.75% and -19.65% for the damaged forest region, and ED > -19.65% for the normal forest region in Yunnan.

The frequency histograms of forest height and stock volume in the three regions—the damaged region, dead region, and normal region, showed that the highest frequency of the forest in the normal region was 6.9% with the corresponding forest height of 25 m. However, a significant rightward shift of the frequency was seen with the maximum of the forest height in the damaged area and dead area of 32 m and 35 m, respectively, and their highest frequencies were 7.6% and 10.1% (Fig. 8a). These data suggest that forest is more susceptible to drought with increasing forest height under drought stress.

In the forest with stock volume of less than  $30 \text{ m}^3/\text{ha}$ , the damaged region accounted for 21% of the forest, and in the forest with stock volume of greater than  $120 \text{ m}^3/\text{ha}$ , the damaged area accounted for 25.5%, indicating that the ratio of damaged region is significantly elevated as the stock volume increase (Fig. 8b). Similarly, the ratio of dead region increased at higher stock volumes. In forests with stock volume of less than  $30 \text{ m}^3/\text{ha}$ , the dead forest accounted for 7.4% of the total forest, and accounted for 12.4% for the stock volume greater than  $120 \text{ m}^3/\text{ha}$ , exhibiting an increase of 5% in damaged ratio (a 67.6% elevation in the absolute value).

To summarize, significant differences in drought response of forest with various heights and stock volumes existed under drought stress. The forest with tall trees (> 32 m) exhibited the greatest damage/dead ratio, whereas the ratio is the least in the forest with short trees (< 25 m). The pattern of the stock volume is similar in the regional



**Fig. 4.** Comparison of the Standardized Precipitation-Evapotranspiration Index (SPEI) spatial distribution in 2001 and 2012. No substantial drought occurred in Yunnan in 2001, but mild to moderate drought was seen in most areas of Yunnan in 2012.

**Table 1**

The correlation of ED average in growing season to forest age, DBH, height, and stock under wet and dry conditions.

Forest variable	Wet			Dry		
	<i>r</i>	<i>N</i>	<i>p</i>	<i>r</i>	<i>n</i>	<i>p</i>
Age(year)	0.18	230	0.007	−0.25	230	< 0.001
DBH(cm)	0.2	230	0.002	−0.28	230	< 0.001
Height(m)	0.14	230	0.017	−0.36	230	< 0.001
Stock Volume(m <sup>3</sup> )	0.32	222	< 0.001	−0.22	222	< 0.001

scale, showing that the damage/dead ratio is elevated as the increases at higher stock volumes, which indicates that the drought response of forests are affected by forest age. Under drought stress, forests with older forest ages exhibit greater vulnerability and are more susceptible to natural adversity.

## 4. Discussion

### 4.1. Differences in drought responses of forests with various ages

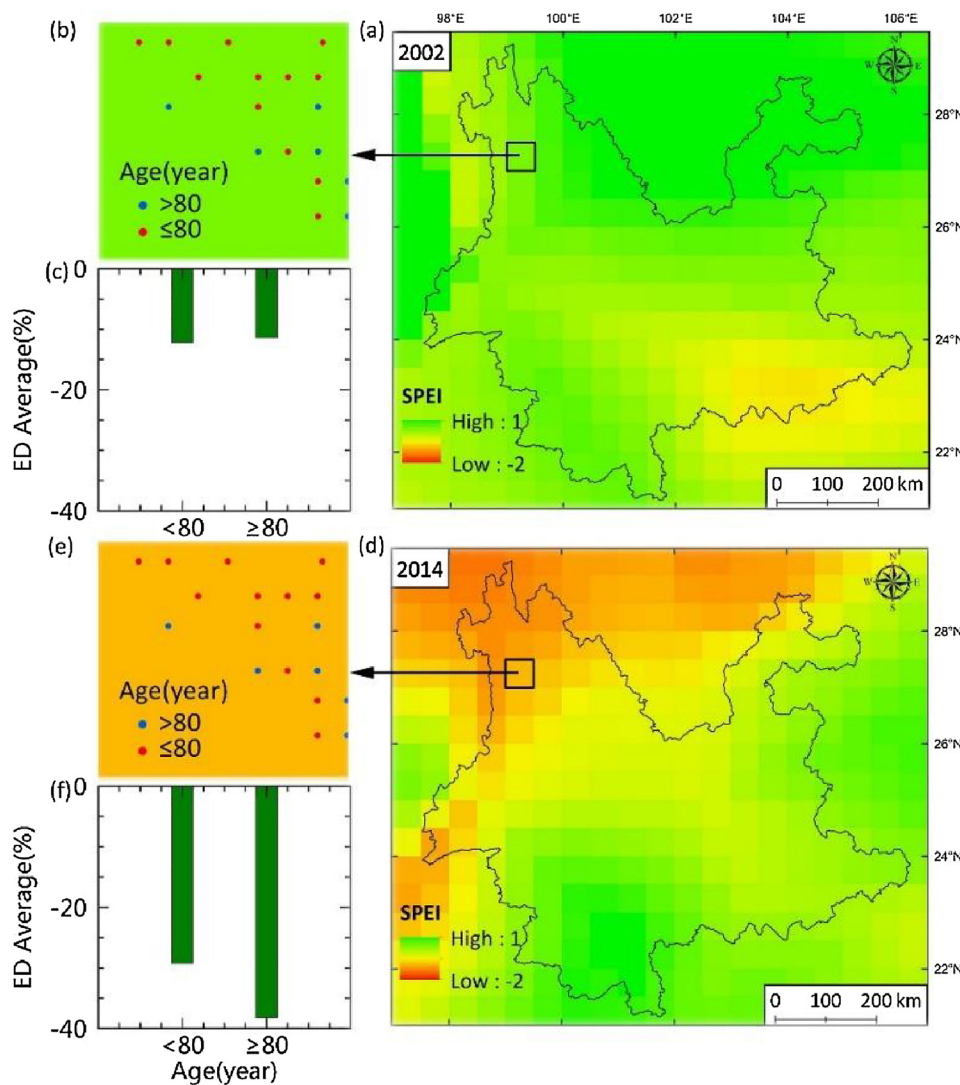
Drought will affect the function and structure of forest ecosystems (Choat et al., 2012), and the forest age is one of the important attributes of forest ecosystems (Zhou et al., 2015). There are differences in the drought responses of forests with various ages, the effect of which can be reflected by multiple potential mechanisms (McDowell et al., 2008). Some studies demonstrate that soil water is less available to the shallow root system of younger trees, resulting in weaker drought tolerance (Nakagawa et al., 2000), whereas other studies show that there exists weaker drought resistance in large trees (Nepstad et al., 2007; Van Nieuwstadt and Sheil, 2005). Our data illustrated that the ED deficit (ED) could reveal regional forest responses to drought stress. The impact on forest was more severe under drought in forests with greater forest age, which is consistent with previous studies. Significant damage and death will occur when the soil water content is less than a certain threshold (Huang et al., 2015). Older forests require more water, so the effects of drought stress are more significant for these forests, and also of extreme drought stress, which is thought to be

associated with their vulnerability to xylem cavitation (Nepstad et al., 2007; Schnitzer and Bongers, 2002). Yunnan experienced a drought with long duration and high intensity (Luo et al., 2016), resulting in the depletion of deep soil water. Therefore, large trees could not absorb enough soil water to maintain growth despite of a developed root system, inducing more significant damage in large trees. In addition, the insufficient transpiration pull might be another reason for the damage to larger trees. The taller the trees are, the longer the vertical water conduction path is from root to canopy, which requires a greater pulling force generated by transpiration. Due to the decrease in transpiration under drought conditions, the pulling force was insufficient to transport water to the canopy, leading to the severe damage in larger trees.

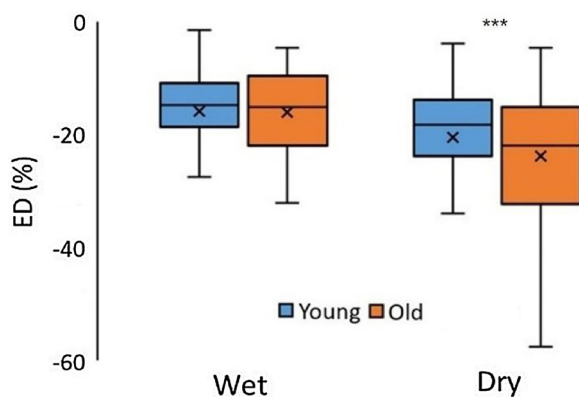
### 4.2. Effect of scale on drought response

Differences in time and spatial scales may have given rise to the controversial understanding of the effects of forest age. Most of the current studies were based on the local scale with a relatively small spatial scale, so they were susceptible to other factors in the local scale (stand conditions and species diversity) (Guarín and Taylor, 2005). At the regional scale, studies on the effects of forest age on drought response is limited, not only due to the impact of spatial heterogeneity and complexity of geographical elements, but also resulting from the lack of the spatial distribution data for forest age over regional scales. Recent studies demonstrated that forest height obtained from the LiDAR could be used as a proxy index for estimating the forest age (Zhang et al., 2014). In the present study, we utilized the spatial distribution pattern of stock volume and forest height as proxies for forest age to study their effects on the differences in drought responses of forests, which compensates for the lack of such research at the regional scale. The recent studies illustrated that satellite observation can serve as an indicator of the drought response (Assal et al., 2016; Dorman et al., 2013), which greatly expands the capacity for research at the regional scale. In the present study, we integrate satellite data and the national inventory data (Luo et al., 2016) to reveal that the effects of drought on forests grew with increasing forest height and stock volume, which is consistent with data from field measurement. In other words,





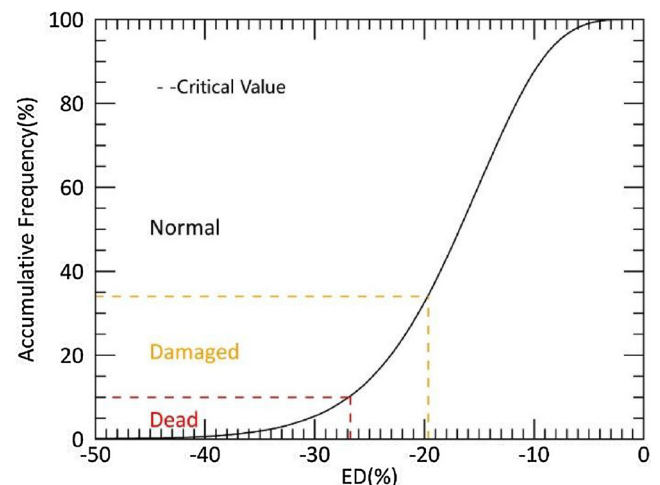
**Fig. 5.** The paired  $t$ -test for the differences in drought responses in forests with various forest ages. (a) and (d) show the spatial distribution of drought for 2002 and 2014 in Yunnan. In the indicated  $0.5^\circ \times 0.5^\circ$  grid, drought did not occur in 2002 (the green grid in (b)), but occurred in 2014 (the yellow grid in (e)). (b) and (e) show the sampling plots in the same SPEI grid divided into younger group (age < 80) and older group (age ≥ 80) (Guo and Ren, 2014; He et al., 2017) based on their forest ages; (c) and (f) show the average ED value individually calculated for younger and older groups to serve as a data pair in the  $t$ -test. A total of 252 data pairs were calculated from 2001 to 2014, including 86 pairs under dry conditions (SPEI < -0.5) and 54 pairs under wet conditions (SPEI > 0.5), and a paired  $t$ -test was performed using these data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)



**Fig. 6.** The difference of ED average in the growing season of younger and older forests under wet and dry conditions (\*\*\*) represents significant at 0.001 level).

older forests face greater drought effects, and this phenomenon does not change across different scales.

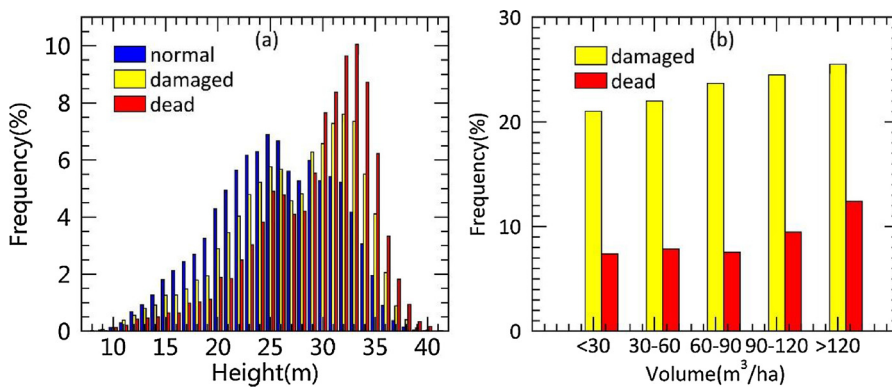
The different drought responses of planted and natural forests are also controversial. Some studies demonstrated that natural forests are more vulnerable and susceptible to drought (Fernández et al., 2009), whereas other studies assert the opposite stance (Broeckx et al., 2014). Our results facilitate the explanation of the controversy. Usually, the forest age, stock volume, and height of natural forests are greater than



**Fig. 7.** The classification for cumulative frequency of ED average.

those of planted forest are, so they are more sensitive to drought stress (Luo et al., 2016).

The data used in the present study include field measurement, national forest inventory, satellite observations, and LiDAR inversion. The LiDAR canopy height dataset provides estimated canopy height values



**Fig. 8.** Difference in drought response of forest with various forest height and stock volume. (a) The histogram of forest height frequency in damaged, dead and normal regions. The taller the trees are, the higher the ratio of damaged/dead forest is; (b) the relationship between damaged/dead ratio of forest and its stock volume. The ratio was elevated as the increase in forest stock volume.

across the land surface. The canopy height in complex topography may not be accurate, but the map employed here is one of the best descriptions of forest vertical structure at regional and global scales currently available (Lefsky, 2010; Duncanson et al., 2010; Simard et al., 2011). The spatial resolution of different kinds of data is not exactly the same, so some deviation in the results is expected. The field measurement samples of forest age are based on a local scale, so there are matching errors between these samples and the satellite data, which are based on a regional scale. The mismatch of scales may result the poor relationships (low absolute value of  $R$ ) between field observations and remote sensing observation (Kerr and Ostrovsky, 2003). However, the reversal of correlation between ED and age (or DBH, Tree Height, Stock) from significantly positive (wet) to significantly negative (dry) is strikingly consistent, supported our results that older forests have greater sensitivity to drought stress. It is difficult to match the scale of the field observations with the scale of satellite observations given limited human, material, and financial resources, leading to the limited sample numbers of forest age. All the field measures are located in the subtropical area (latitude below  $30^\circ$  N) and the treeline altitude in this region is above the highest altitude—no visible treeline. To illustrate the point, we picked the top two plots with the highest altitude ( $98.65^\circ\text{E}$ ,  $28.62^\circ\text{N}$ , elevation = 4060 m and  $99.33^\circ\text{E}$ ,  $27.97^\circ\text{N}$ , elevation = 4120 m), positioned them at google earth according to their latitude and longitude, and all of the two are below visible treeline. Also our results were based on standardized vegetation index (ED), which had removed the influence of site specificity (including altitude), so the potential impact of elevation were ignored in this research. Due to the lack of data, this approach didn't fully encompass all drought-related caused of tree mortality, such as bark thickness, insect infestations and forest wildfires (McHugh and Kold, 2003). Those factors might increase the uncertainty of the result.

In addition, due to the lack of drought distribution maps in the study region, the EVI deficit was classified based on the statistical data of forest damage/dead ratio to define regions facing different drought impacts (Luo et al., 2016). Because the ground survey data of the Forestry Department of Yunnan and satellite data were not exactly matched, there were inevitable errors in the designation of regions, which require validation through high-resolution remote sensing image (such as Google Earth) as well as field investigations to eliminate the uncertainty.

#### 4.3. Management implications

Remote sensing data can be used to study the responses of vegetation to climate change on regional and global scales (Wu et al., 2015), especially the effects of extreme climate events (such as drought) on vegetation (Vicente-Serrano et al., 2013). Drought stress can influence productivity (Ciais et al., 2005) and the growth of forests (Huang et al., 2015), and further affect the carbon sink function of forest ecosystems. However, the variation in age is often ignored in the study of drought

responses in forest, so potential deviation occurs when evaluating the effects of drought on forests with different ages. In the present study, we integrated multiple sources, and showed that the results of different spatial scales are in complete agreement under drought stress. Therefore, the drought stress is more severe as the forest age increases, regardless of scale.

From an economic point of view, the volume of forests can provide greater economic benefits with increases in forest age. However, the IPCC5 report (Stocker, 2014) showed that the frequency and duration of drought will increase in the future worldwide, which suggests that older forests will likely face a higher risk of death and degradation with future climate change. Therefore, to determine how to effectively manage forests to maximize their value, managers need to consider the effects of age on drought-related risks when making decisions for mitigating the effects of climate change on forests (Bellassen and Luyssaert, 2014).

#### 5. Conclusion

Human activities such as afforestation significantly change the age structure of forest ecosystems. Investigating the characteristics of drought responses in forests with different ages is the basis for accurately assessing the effects of future climate change on forest ecosystems. In this study, we used the EVI to calculate the ED, which can show the effects of drought on the growth status of forests. In addition, we analyzed the characteristics of drought responses in forest ecosystems with different forest ages, stock volumes, and heights. Our data demonstrate that drought has a significant impact on the forest ecosystem in Yunnan Province, and that the degree to which it affects a forest depends on the forest age, showing a substantial age effect. Under the same drought stress, older forests are more vulnerable and susceptible to drought, exhibiting that the older the forest, the higher the forest, and the larger the stock volume, the more severe the influence will be. This pattern holds true across different spatial scales. Considering the increase in the frequency and duration of drought in the context of global climate change, we need to pay more attention to age in forest management and risk assessments in the future.

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